Available online at www.sciencedirect.com
ScienceDirect
Procedia Materials Science 5 (2014) 164 – 172
Procedia Materials Science
www.elsevier.com/locate/procedia

International Conference on Advances in Manufacturing and Materials Engineering, AMME 2014

An energy absorption behaviour of foam filled structures

Dipen Kumar Rajak[1*], L.A.Kumaraswamidhas[1], S.Das[2]

[1]Department of Mining Machinery Engineering,
Indian School of Mines, Dhanbad, Jharkhand-826004, (INDIA)
[2]Advanced Materials and Processes Research Institute, Bhopal- 462026, (INDIA)

Abstract

Aluminium foam is an isotropic permeable metal of cellular construction in the order of 75-85 vol. % of the pores. In turn the mechanical and physical properties depend on the density of foam, i.e. lies in the range in between 0.5-2.1 gm/cm^3. Aluminium foam filled structures are used in crash energy absorption, noise absorbing and vibration damping applications. In this article, the compressive deformation behaviour of rectangular aluminium foam filled and rectangular empty mild steel samples are analyzed to identify the supplementary energy absorption rate per unit volume in diverse strain rate, by means of the compressive testing.

© 2014 Elsevier Ltd. This is an open access article under the CC BY-NC-ND license
(http://creativecommons.org/licenses/by-nc-nd/3.0/).
Selection and peer-review under responsibility of Organizing Committee of AMME 2014

Keywords: Aluminium foam, Rectangular mild steel, Mechanical testing.

1. Introduction

Metal foams have a lot of applications in different fields such as lightweight construction, crash energy absorption, thermal insulation and acoustic management. Aluminium foams with a soaring fraction of porosity which is a quickly emerging class of novel materials for an assortment of mass production [Gibson et al. 1997; Simone et al. 1998; Kenny 1996; Jin et al. 1990; Akinyama et al. 1987; Mishra et al. 2005; Falahati et al. 1997; Mondal et al. 2011]. Aluminium foam is a cellular construction of a solid metal, containing an outsized volume portion of gas-filled pores. The pores can be sealed (closed-cell foam), or it can form an interconnected network (open-cell foam) [Hangai et al. 2013; Banhart et al. 2001; Baumeister et al. 1997].

* Corresponding author. Tel.: +91-9470307646; fax: +91-326-2296563.
E-mail address: dipen.pukar@gmail.com

2211-8128 © 2014 Elsevier Ltd. This is an open access article under the CC BY-NC-ND license
(http://creativecommons.org/licenses/by-nc-nd/3.0/).
Selection and peer-review under responsibility of Organizing Committee of AMME 2014
doi:10.1016/j.mspro.2014.07.254

The defining feature of metal foams is a very high porosity of range in between 75–85% of the volume consists of an empty space making these ultra-light materials shown in fig. 1 [Baumeister et al. 1997; Hall et al. 2000]. The luminosity weight material in combustible ecologically nontoxic and directly recycling. Lightweight aluminum foam filled rectangular panels; crash energy dissipation and head impact damage alleviation, to dwindle passenger impact injury were explored [Melzer et al. 1998; Banhart et al. 1998; Banhart et al. 1995]. It has the competence of absorbing significant impact energy by a large plastic deformation under quasi-static and dynamic loading, making it ideal construction protectors and energy absorbers [Banhart et al. 1995; Banhart et al. 2005; Ramchandra et al. 2003; Paul et al. 2000]. In terms new strategies of crash energy absorption and new equipment have provided a safer nomadic environment; during the test found that aluminum foam filled structures have outstanding performance in terms of compressive load, vibration damping, and relatively good crash energy absorption. One of their main and important performances is structural applications with a unique shape of compressive stress–strain response.This response consists of three distinct regions; linear elastic region, plateau region and densification region.Mechanical properties of aluminium foam depend mainly upon the two basic factors, (1) Cell wall material and (2) The presence of gas/fluid inside the cell [Banhart et al. 1998; Banhart et al. 1995; Banhart et al. 2005; Ramchandra et al. 2003; Paul et al. 2000], compression deformation behavior of aluminium foam filled section is deliberate by different investigators [Das et al. 2012] and it is revealing that the plateau stress is insensitive to the strain rate [Patel et al. 2011; Davies et al. 1983; Baumeister et al. 1998]. In this article eight different rectangular section samples were taken for compression testing and processes their own dimensions, each sample gives different strain-stress curve under the compression load. The energy absorption of mild steel foam filled section increase with increasing plateau stress (σ_{Pl}) in same sample. When compare with empty mild steel section to foam filled mild steel section energy absorption increase considerably.

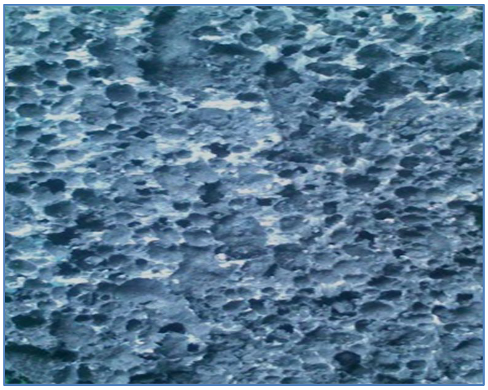


Fig. 1. An example of 75-85% porous aluminium foams.

Nomenclature	
σ	Stress
ε	Strain

1.1. Aluminium foam properties

Foams of diverse production technologies can contain different properties, even if it made out of an identical alloy than therefore for an application it is determined to list all the required properties of the foam. The advantage of foam becomes perceptible, when bending stresses are measured as a utility of weight in lightweight constructions and relatively high stiffness and lower density. It is essential to note that if only direct strength is measured, foams often have a comparable than solid material of the similar weight [Hangai et al. 2013; Banhart et al. 2001; Baumeister et al. 1997]. The mass delivery of cellular structures increases at the whole moment of inertia of the material, giving a far higher specific stiffness and strength than for the corresponding weight of vastness metal.

1.2. Mechanical properties

Various literature studies have been undertaken on the mechanical properties of Al foams. A wide review of the understanding of the mechanical behavior of a wide range of cellular solids is provided [Gibson et al. 1997; Simone et al. 1998; Kenny 1996], others have carried out test to study the behavior of metallic foams under diverse loading conditions, particularly the properties of Al foams under impact loading. The chance of controlling the load-displacement behavior by a proper selection of cellular geometry, matrix material and relative density make foam a supreme material for energy absorbing structure. Along with the some mechanical testing methods existing, [Falahati et al. 1997] uniaxial compressive mechanical test is generally used to calculate the compressive behavior and energy absorbed of these foams. The stress-strain curve of closed-cell Al-alloy foam shows either plastic or brittle fracture depending on foam manufacture and microstructure [Hangai et al. 2013]. Al-alloy foam is regularly used as stuffing material in lightweight structures subject to crash load and aural insulation devices. The energy absorption aptitude of this foam can be well expected from the stress-strain compression behavior of the materials [Melzer et al. 1998].

2. Experimental and Methods

2.1. Material properties

Two samples, i.e. rectangular empty mild steel and rectangular Al foam filled section was studied in this work. Empty rectangular mild steel sample all specification and density shows in Table 1, and Al rectangular foam filled section specification and density shows in Table 2, during the compression testing consider empty rectangular section is 98% pores and as well as Al rectangular foam filled section 80-85% pores.

Table 1.Sample specification and density of rectangular empty mild steel samples.

Sl. No.	Height (mm)	Mass (g)	Width (mm)	Thickness (mm)	Cross Sectional Area (mm^2)	Volume (mm^3)	Density (g/cm^3)
01	36.63	41.55	26.41	25.52	673.98	24687.88	1.683
02	36.41	40.34	26.51	25.38	672.82	24497.37	1.646
03	35.56	39.24	26.50	25.42	673.63	23954.28	1.638
04	35.01	38.70	26.61	25.34	674.30	23607.24	1.639

Table 2. Sample specification and density of rectangular Al foam filled mild steel samples.

Sl. No.	Height (mm)	Mass (g)	Width (mm)	Thickness (mm)	Cross Sectional Area (mm^2)	Volume (mm^3)	Density (g/cm^3)
01	37.75	51.90	26.86	25.73	691.11	26089.40	1.989
02	38.07	53.96	26.76	25.70	687.73	37109.91	1.454
03	38.99	55.37	26.92	25.74	692.92	38366.98	1.443
04	38.81	55.11	26.85	25.79	692.46	38161.47	1.444

2.2. Compression test

Foam sample prepared by melt route using a patented process of CSIR-AMPRI Bhopal .The foam sample were cut conforming to the size of the mild steel rectangular section .The foam piece were tightly fitted inside the mild steel rectangular section and were tested for compressive behavior. Rectangular foam filled section and mild steel rectangular empty section is performed on an Instron-8801 machine at various strain rate from 10^{-3}/s to 1/s for the compressive test .The dimension of empty mild steel sample prepared of thickness 25.52 mm, width 26.41 mm and height 36.63 mm and mild steel sample filled with Al foam is prepared of thickness 25.73 mm, width 26.86 mm and height 37.75 mm. The yield stress and plateau stress were measured from stress-strain diagram. An Instron-8801 Shown in Fig. 2 (a) and (b) used during compression test.

a

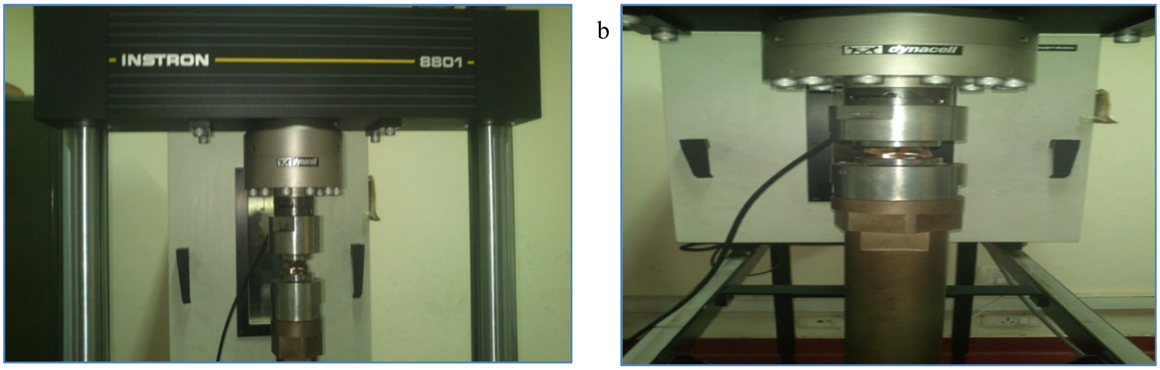


Fig. 2. (a) An initial compression test of sample; (b) after compression test of sample.

a

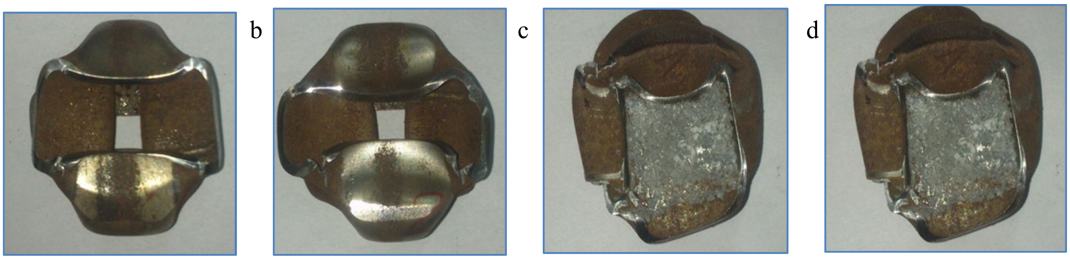


Fig. 3. (a, b) empty mild steel samples; (c, d) Al foam filled samples; both are after compression test

3. Result and Discussion

Energy absorbing per unit volume of foam filled sample and empty sample is calculated by measuring the area of plateau stress under the stress-strain diagram. The energy absorbed by foam filled sections is a function of crack of cell wall and the energy released due to friction between cell wall. The energy absorbed per unit volume by foam sample and without foam sample is found diverse at various strain rates.

3.1. Effect of strain rates on the energy absorption of Al foam filled Ms sample and empty Ms sample strain rate: 0.001

Empty mild steel sample prepared of thickness 25.52 mm, width 26.41 mm and height 36.63 mm. The area of sample is 673.98 mm^2. While other mild steel sample filled with Al foam is prepared of thickness 25.73 mm, width 26.86 mm and height 37.75 mm. The area of Al foam filled mild steel sample is 691.11 mm^2. The samples are shown in fig. 3 (a, b, c & d).These two samples are compressed under strain rate of 0.001; the stress-strain diagram of samples tested under strain rate of 0.001 is shown in fig. 4 (a) and (b). The absorbed energy per unit volume is calculated by measuring the area under the stress-strain diagram. Empty mild steel sample absorbs energy up to 24 MJ/m^3 but Al foam filled mild steel sample absorbs energy up to 26.4 MJ/m^3. The absorbed energy of Al foam filled mild steel sample is improved by 10% under strain rate of 0.001.

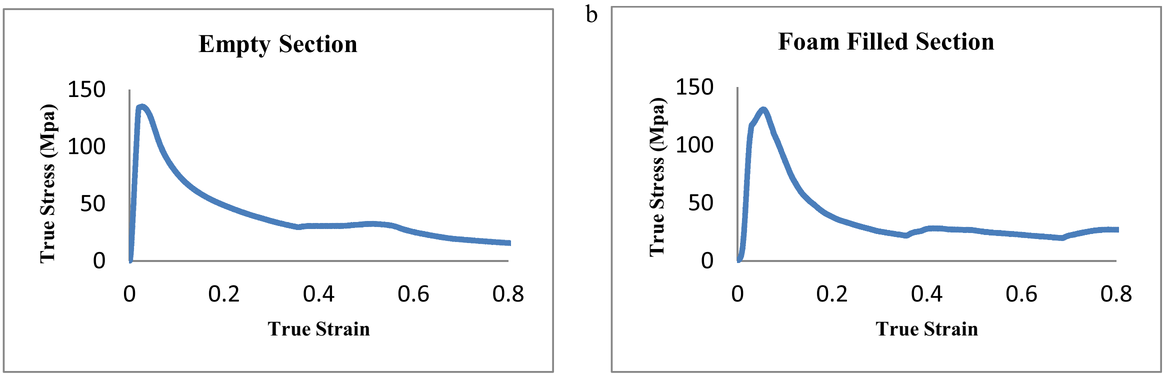
a b


Fig.4. (a) stress-strain diagram for empty section; (b) stress-strain diagram for foam filled section, strain rate: 0.001.

3.2. Effect of strain rates on the energy absorption of Al foam filled Ms sample and empty Ms sample strain rate: 0.01

Empty mild steel sample prepared of thickness 25.38 mm, width 26.51 mm and height 36.41 mm. The area of sample is 672.82 mm^2. While other mild steel sample filled with Al foam is prepared of thickness 25.70 mm, width 26.76 mm and height 38.07 mm. The area of Al foam filled mild steel sample is 687.73 mm^2. The samples are shown in fig. 3 (a, b, c & d).These two samples are compressed under strain rate of 0.01; the stress-strain diagram of samples tested under strain rate of 0.01 is shown in fig. 5 (a) and (b). The absorbed energy per unit volume is calculated by measuring the area under the stress-strain diagram. Empty mild steel sample absorbs energy up to 25 MJ/m^3 but Al foam filled mild steel sample can absorb energy up to 32 MJ/m^3. The absorbed energy of Al foam filled mild steel sample is improved by 28% under strain rate of 0.01.

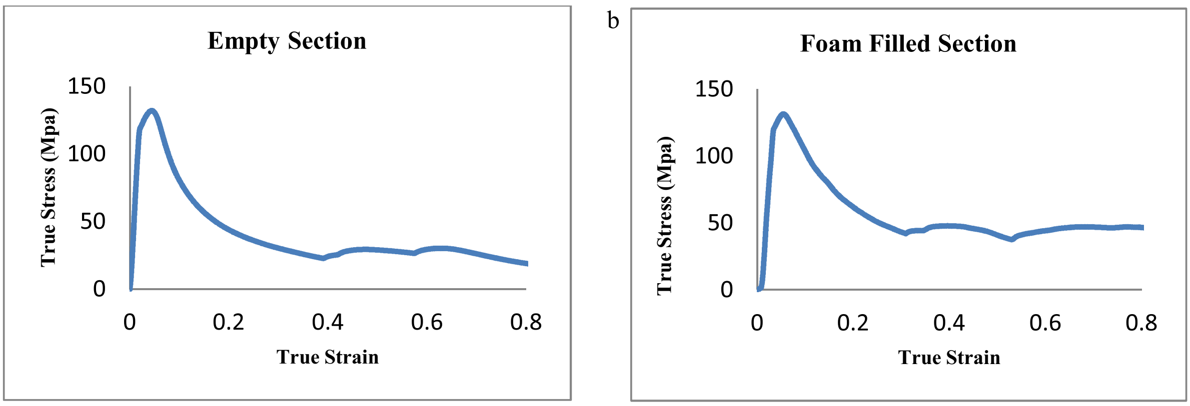
a b


Fig.5. (a) stress-strain diagram for empty section; (b) stress-strain diagram for foam filled section, Strain rate: 0. 01

3.3. Effect of strain rates on the energy absorption of Al foam filled Ms sample and empty Ms sample strain rate: 0.1

Empty mild steel sample prepared of thickness 25.42 mm, width 26.50 mm and height 35.56 mm. The area of sample is 673.63 mm^2. While other mild steel sample filled with Al foam is prepared of thickness 25.74 mm, width 26.92 mm and height 38.99 mm. The area of Al foam filled mild steel sample is 692.92 mm^2. The samples are shown in fig. 3 (a, b, c & d). These two samples are compressed under strain rate of 0.1; the stress-strain diagram of samples tested under strain rate of 0.1 is shown in fig. 6 (a) and (b). The absorbed energy per unit volume is calculated by measuring the area under the stress-strain diagram. Empty mild steel sample can absorb energy up to21.6 MJ/m^3 but Al foam filled mild steel sample can absorb energy up to 32 MJ/m^3. The absorbed energy of Al foam filled mild steel sample is improved by 48% under strain rate of 0.1.

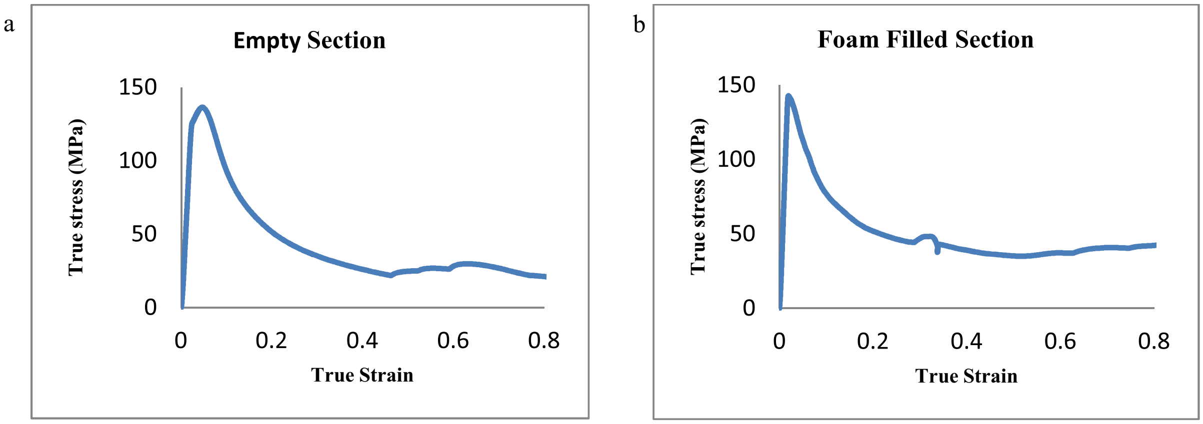


Fig.6. (a) stress-strain diagram for empty section; (b) stress-strain diagram for foam filled section, Strain rate: 0.1

3.4. Effect of strain rates on the energy absorption of Al foam filled Ms sample and empty Ms sample strain rate: 1

Empty mild steel sample prepared of thickness 25.34 mm, width 26.61 mm and height 35.01 mm. The area of sample is 674.30mm^2. While other mild steel sample filled with Al foam is prepared of thickness 25.79 mm, width 26.85 mm and height 38.81 mm. The area of Al foam filled mild steel sample is 692.46 mm^2. The samples are shown in fig. 3 (a, b, c & d). These two samples are compressed under strain rate of 1; the stress-strain diagram of samples tested under strain rate of 1 is shown in fig. 7 (a) and (b). The absorbed energy per unit volume is calculated by measuring the area under the stress-strain diagram. Empty mild steel sample can absorb energy up to 25.6 MJ/m^3 but Al foam filled mild steel sample can absorb energy up to 33.6 MJ/m^3. The absorbed energy of Al foam filled mild steel sample is improved by 31% under strain rate of 1.

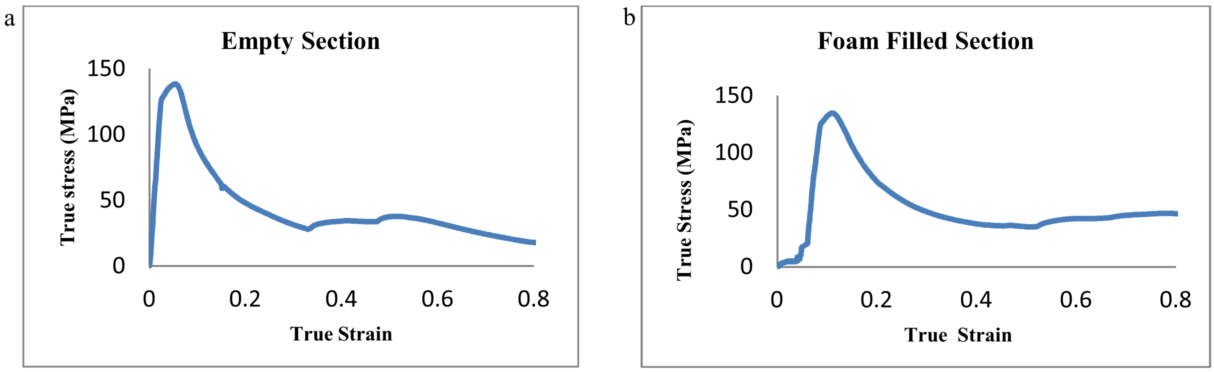


Fig.7. (a) stress-strain diagram for empty section; (b) stress-strain diagram for foam filled section, Strain rate: 1.

3.5. Energy absorption

The energy absorbed per unit volume with foam sample and empty sample is found at different strain rates. The absorbed energy per unit volume is calculated by measuring the area under the stress-strain diagram. The area under the stress-strain diagram is calculated by plateau stress. The plateau stress in the stress-strain diagram is constant throughout the densification region. Shown in fig. 8,

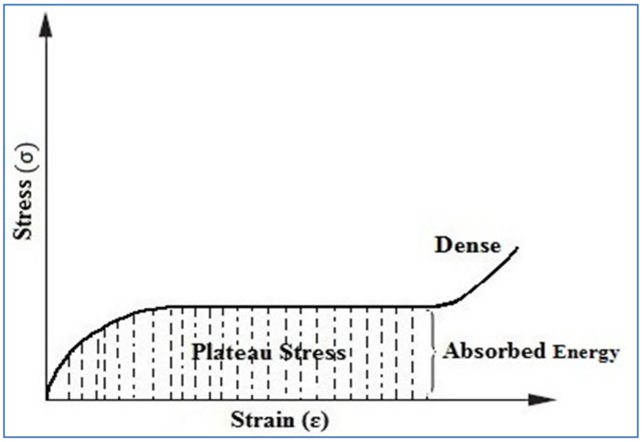


Fig. 8.Shows example of stress-strain diagram for aluminium foam energy absorption.

The percentage increase in the energy absorption is calculated by the difference of Al filled mild steel sample and mild steel sample divided by the empty mild steel sample.

It is observed from Table 3 that energy absorption increases with strain rate, and the energy absorption of Al foam filled samples is more than empty samples. When the strain rate is increased from 0.001 to 1, energy absorption of Al foam filled sample increases from 26.4 MJ/m^3 to 33.6 MJ/m^3 and the energy absorption of empty mild steel sample increases from 24 MJ/m^3 to 25.6 MJ/m^3.The energy absorption of Al foam filled mild steel sample is increases by 10%, 28%, 48%, and 31% than empty mild steel samples at strain rate of 0.001, 0.01, 0.1, 1 respectively. The above results indicates that Al foam filled mild steel sample at 0.1 strain rate shows highest improvement in energy absorption of mild steel sample.

Table 3. Shows energy absorption of Al foam filled rectangular and empty rectangular mild steel sample at various strain rate.

Strain Rate	Empty Section (Plateau Stress MPa)	Foam Filled Section (Plateau stress MPa)	Improvement in The Plateau Stress (Plateau stress MPa)
0.001	24	26.4	2.4
0.010	25	32	7
0.100	21.6	32	10.4
1.000	25.6	33.6	8

3.6 Microstructure of foam

The microstructure of foam sample is analyzed using scanning electron microscope (SEM) (Model: Hitachi S-3400N, Japan).These micrographs are required to identify aluminium foam behavior under compression load.

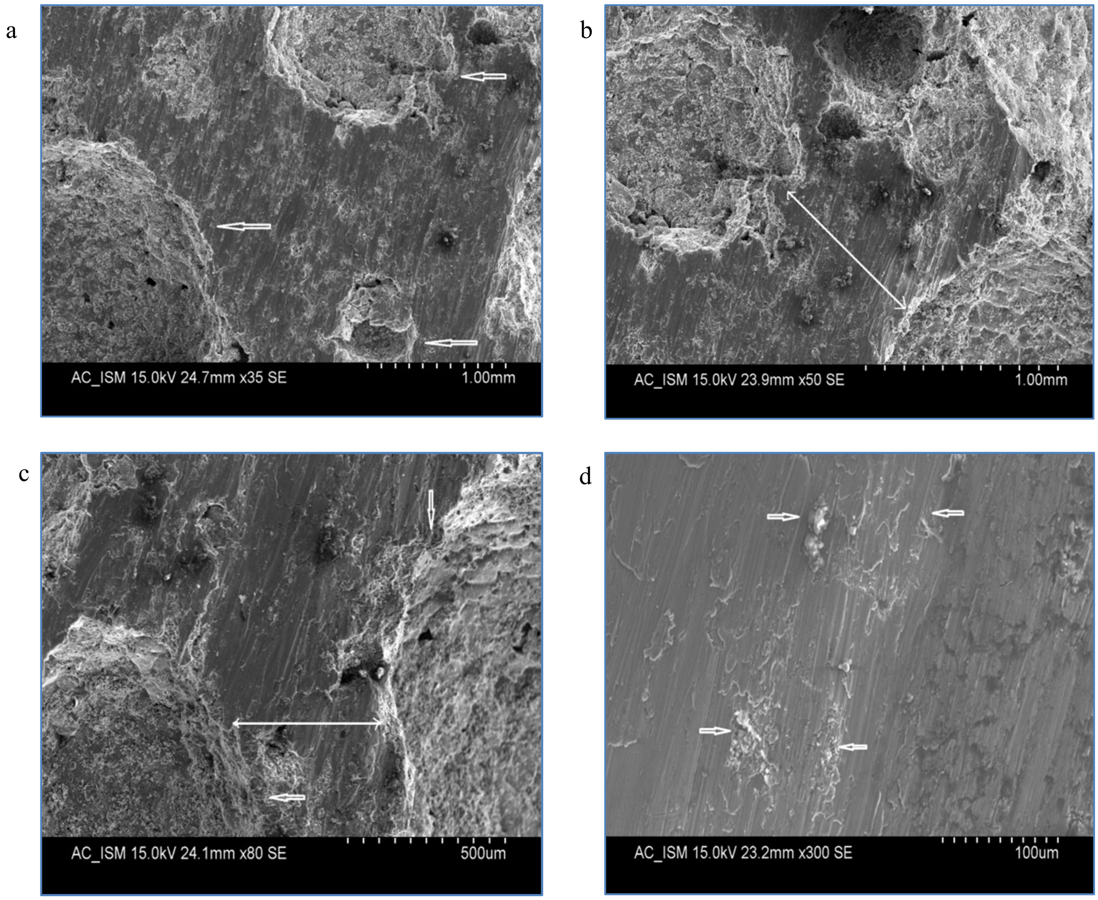


Fig.9 (a) SEM micrograph of Al alloy foam showing cell; (b) Higher magnification micrograph showing cell wall; (c) SEM micrograph of Al alloy foam showing cells and wall; (d) Higher magnification micrograph of cell wall showing allocation of SiC particle in Al alloy.

4. Conclusions

The compressive stress-strain diagram shows three distinct regions, linear elastic region, plateau region and densification region. The plateau stress of Al foam filled mild steel samples increases in strain rate 0.1. This increase in plateau stress increases energy absorption. The energy absorption of Al foam filled mild steel sample and empty mild steel sample increases from 26.4 MJ/m^3 to 33.6 MJ/m^3 and 24 MJ/m^3 to 25.6 MJ/m^3 respectively with increase in strain rate. The energy absorption of Al foam filled mild steel sample is increased by 1.56 times as compared to empty mild steel samples at strain rate of 0.1. This gives maximum increase of energy absorption Al foam filled mild steel samples from empty mild steel samples at different strain rate.

Acknowledgements

The authors wish to express their gratitude to Light Weight Metallic Material Laboratory, CSIR-AMPRI Bhopal.

References

L.J. Gibson, M.F. Ashby, 1997, Cellular Solids: Structure and Properties, 2nd edition, Cambridge University Press, Cambridge, UK, pp. 528.
A.E. Simone, L.J. Gibson, 1998, Aluminium Foams Produced by Liquid State Processes, Acta Mater. 46, 3109–3123.

L.D. Kenny, 1996, Mechanical Properties of Particles Stabilized Aluminium Foam, Mater. Sci. Forum 217–222, 1883–1890.

I. Jin, D. Kenny, H. Sang, 1990, Method of Producing Lightweight Foamed Metal, U.S. Patent No. 4 973 358.

S. Akinyama, S. Ueno, K. Imagawa, A. Kitahara, S. Nagata, K.M. Amagasaki, T.N. Amagasaki, M.I. Amagasaki, 1987, Foamed metal and method of producing same, U.S. Patent No. 4 713 277.

R. S. Mishra and Z. Y. Ma, 2005, Effect of Die Material on Compressive Properties of Open-Cell Porous Aluminum Fabricated by Friction Powder Compaction Process, Mater. Sci. Eng. R-Rep. 50, 1-78

A. Falahati, 1997, Feasibility Study for the Production of Iron-Based Metallic Foams, Technische University, Wien, Master Thesis.

D.P.Mondal, N. Jha, A. adkul, S. Das, M.S.Yadav,P.Jain, 2011, Effect of Calcium Addition on The microstructure and Compressive Deformation Behaviour of 7178 Aluminum Alloy, Mater.and Design 32(5), 2803-2812.

Y.Hangai, M.Saito, 2013, Fabrication of an Al Foam/Dense Steel Composite by Friction Welding, Materials Transactions,54(6), 1012-1017

J. Banhart, 2001, Manufacture, Characterization and Application of Cellular Metals and Metal Foams, Progress in Materials Science 46, 559-632.

J.Baumeister, J. Banhart, B.Weber, 1997, Aluminium Foams for Transport Industry, Materials & Design 18(4/6), 217-220.

W. I.Hall, M.Guden, J. C.Yu, 2000, Crushing of Aluminium Closed Cell Foams: Density and Strain Rate Effects, Materialia, 43, 515-521.

A.Melzer, J. Banhart, J. Baumeister, M. Weber, 1998, German Patent 19813176.

J. Banhart, J. Baumeister, 1998, Production Methods for Metallic Foams, Porous and Cellular Materials for Structural Applications, MRS Symposium Proceedings, 521, 121.

J. Banhart, J. Baumeister, M. Weber,1995, Powder Metallurgical Technology for the Production of Metal Foam, Proc.European Conf. on Advanced PM Materials,(Gct.23 - 25,), 201.

J. Banhart, 2005, Aluminium Foams for Lighter Vehicles, International Journal of Vehicles Design, 31 (2/3), 125.

S. Ramchandra, U. Ramamurty, P. Sudheer Kumar, 2003, Impact Energy Absorption In an Al Foam at Low Velocities, Scripta Mater, 49(8), 741-745.

A. Paul, U. Ramamurty, 2000, Strain rate Sensitivity of a Closed-cell Aluminium foam, Mater.Sci. Engg. 281, 1-7.

S. Das,B.K. Prasad, 2012,Al and Mg based Lightweight Metallic Materials for Automobile Applications, Invertis Journal of Science and Technology, 5(2), 1-10.

A. Patel, S. Das, B.K. Prasad, 2011, Compressive Deformation of Al (2014) – 10wt%. Sic Composites: Effect of Strain Rates and Temperatures, Material Science. & Eng.530, 225-232.

G.J. Davies, Shu Zhen, 1983, Metallic Foams; Their Production, Properties and Applications, J.Mater. Sci. 18, 1899–1911.

J. Baumeister, J. Banhart, 1998, Deformation Characteristics of Metal Foam, J.Mater. Sci. 33, 1431-1440.